

Nearly isotropic upper critical fields in a $\text{SrFe}_{1.85}\text{Co}_{0.15}\text{As}_2$ single crystal

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Abstract

We study temperature dependent upper critical field H_{c2} of a $\text{SrFe}_{1.85}\text{Co}_{0.15}\text{As}_2$ single crystal ($T_c=20.2$ K) along ab -plane and c -axis through resistivity measurements up to 50 T. For the both crystalline directions, H_{c2} becomes nearly isotropic at zero temperature limit, reaching ~ 48 T. The temperature dependence of the H_{c2} curves is explained by interplay between orbital and Pauli limiting behaviors combined with the two band effects.

Keywords: Superconductivity, iron-pnictides, upper critical field

1. Introduction

The observation of high temperature superconductivity in iron-pnictides has triggered a surge of research activity in recent years to understand basic physical properties as well as pairing mechanism of the new superconducting system [1]. Upper critical field H_{c2} is one of key parameters to indicate underlying superconducting pairing strength and related electronic structure. Nearly isotropic $H_{c2}(0)$ has been recently observed in both a hole-doped $(\text{Ba,K})\text{Fe}_2\text{As}_2$ crystal and an electron doped $\text{SrFe}_{1.8}\text{Co}_{0.2}\text{As}_2$ thin film [2, 3]. Moreover, as the parent material shows quasi-two dimensional Fermi surfaces, nearly isotropic $H_{c2}(0)$ is unusual and in sharp contrast with the case of cuprates. These experimental findings raise a couple of puzzles regarding the physics behind: (1) is the phenomenon an intrinsic property of the whole iron-pnictides? (2) why are they insensitive to the change of electronic structure driven by hole- and electron-doping? (3) can the orbital limiting effect only, combined with multiband effects, explain the low temperature behavior? To answer these questions, it is quite desirable to check the H_{c2} behaviors in various forms of iron-pnictides. In this study, we have determined $H_{c2}(T)$ curves up to 50 T in an electron doped $\text{SrFe}_{1.85}\text{Co}_{0.15}\text{As}_2$ single crystal. We found nearly isotropic $H_{c2}(0)$ in the single crystal, consistent with the case of the Co 20 %-doped thin film. Our results indicate that the isotropic $H_{c2}(0)$ behavior is quite robust, independent of dopant types or amount as well as disorders in the ‘122’ system.

2. Experiments

Single crystals of $\text{SrFe}_{2-x}\text{Co}_x\text{As}_2$ were prepared by the Sn-flux method as described in detail in previous works [4, 5]. X-ray diffraction indicated a single phase without noticeable impurities and energy-dispersive X-ray spectroscopy showed $x =$

0.15. The magnetic field dependence of resistivity was measured at an isothermal condition by use of a short pulse magnet with a 20 ms decay time at NHMFL, Los Alamos National Laboratory. Different pieces showing same T_c from one batch were measured in each field direction. Data were taken during the H down-sweep using a lock-in amplifier at 100 kHz. The resistivity curves in rising and decreasing H were well overlapped at overall temperatures except 3 - 7 K, indicating isothermal temperature conditions are achieved during the pulse at overall temperatures except ones between 3 and 7 K.

3. Result and discussion

Figure 1 shows the resistivity curves for H parallel and perpendicular to c -axis (denoted by $H \parallel c$ and $H \perp c$, respectively). H_{c2} at a given temperature was determined by the field position at which 90 % normal state resistivity is realized. T_c was estimated to be 20.2 K with this criterion. Figure 2 depicts the evolution of H_{c2} for both $H \parallel c$ and $H \perp c$. When H_{c2} curve was estimated with conditions of 50 % or 10 % normal state resistivity, the determined shapes were nearly identical to the one in Fig. 2 except nearly parallel shift of H_{c2} less than 5 T.

For $H \parallel c$, H_{c2} is nearly linear in temperature, while for $H \perp c$, H_{c2} has an upward curvature with temperature and shows saturation at low temperatures. Moreover, at overall temperatures, H_{c2} for $H \perp c$ is higher than for $H \parallel c$, showing more robust superconductivity for $H \perp c$. At the high temperature region near T_c , the orbital limiting is thought to be a main mechanism for determining H_{c2} . The orbital limiting effect refers to opposite Lorentz forces on Cooper-paired electrons having reversed spatial momentum. From the initial slope near T_c , we can estimate the orbital limiting field, $H_{c2}^{\text{orb}}(0)$ in each direction. $H_{c2}(T)$ slope near T_c is 3.73 T/K and 2.45 T/K in $H \parallel c$ and $H \perp c$, respectively. According to Werthamer-Helfand-Hohenberg (WHH) formula, i.e $H_{c2}^{\text{orb}}(0) \approx -0.69 \partial H_{c2}(T) / \partial T|_{T=T_c}$, $H_{c2}^{\text{orb}}(0)$ is 52.7

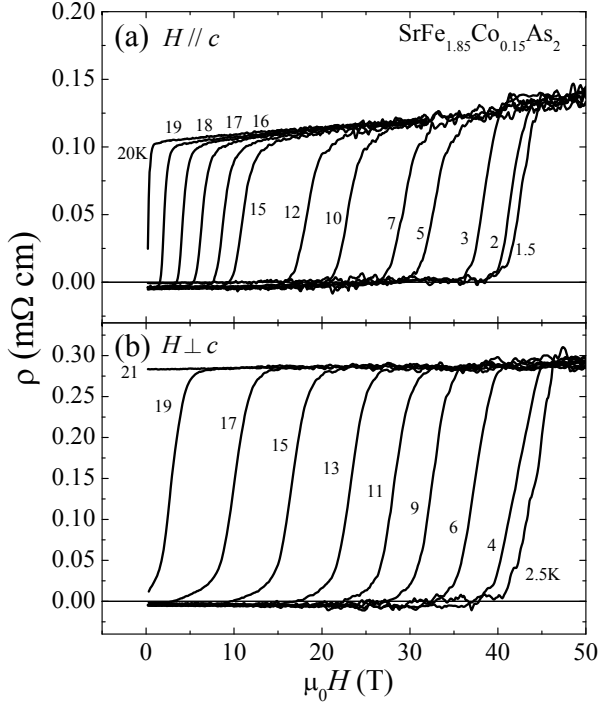


Figure 1: Resistivity measured under pulsed magnetic field up to 50 T at a fixed temperature. H was applied (a) along c -axis ($H \parallel c$) and (b) perpendicular to c -axis ($H \perp c$).

T and 34.6 T in each direction. The difference in $H_{c2}^{\text{orb}}(0)$ should be related to the difference in quasiparticle effective mass (or superconducting coherence length) for each crystallographic direction. From the high temperature behavior, it is thus expected that the in-plane superconducting coherence length is larger than one along the c -axis.

The dotted lines in Fig. 2 denote the temperature dependent WHH curve with $\alpha = \lambda_{so} = 0$. According to the fit results, we note that the actual $H_{c2}(0) \approx 48$ T is larger than $H_{c2}(0)$ for $H \parallel c$, while it is smaller than $H_{c2}(0)$ for $H \perp c$. Unusually large $H_{c2}(0)$ beyond the predicted $H_{c2}^{\text{orb}}(0)$ for $H \parallel c$ is associated with its linear increase down to zero temperature. This linearly increasing H_{c2} for $H \parallel c$ has been commonly observed in other ‘122’ materials studied so far [2, 3]. Indeed, the WHH formula cannot describe this linearly increasing behavior effectively as seen in the fitted curve. As studied recently [3], the two band effects might have to be incorporated to properly explain the almost linearly increasing H_{c2} shape for $H \parallel c$.

One conspicuous feature in Fig. 2 is the nearly isotropic $H_{c2}(0) \approx 48$ T for both field directions. This is quite consistent with the results in an epitaxial thin-film [3]. When the ratio γ between the two H_{c2} values is estimated from the interpolation of the curves in Fig. 2, γ is around 1.7 near T_c and monotonically decreases down to 1.05 at the zero temperature limit. Our observation implies that the nearly isotropic H_{c2} behavior is not sensitive to carrier doping and disorder. According to the fit results of the WHH formula for $H \perp c$, the actual $H_{c2}(0) \approx 48$ T is slightly, but clearly, less than the predicted $H_{c2}^{\text{orb}}(0) = 52.7$ T.

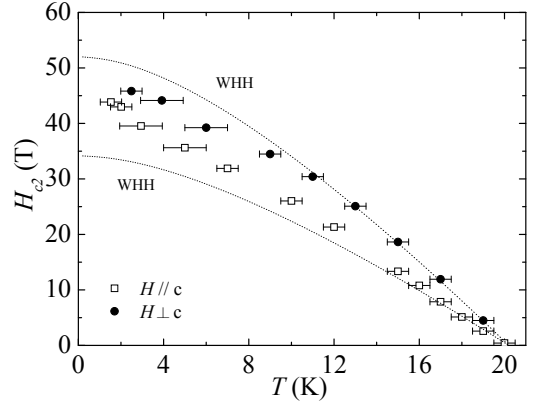


Figure 2: Temperature dependence of upper critical field H_{c2} . The dashed lines are the predictions of the WHH curve.

This experimental fact suggests the need for the other mechanism, i.e., Pauli limiting to make the upper critical field saturate at low temperatures.

The Pauli limiting is based on the Zeeman effect on a spin-singlet Cooper pair so that it should be isotropic for any field direction. The Pauli limiting field H_p of a BCS superconductor is estimated to be $1.84k_B T_c = 37.5$ T in our sample. This value is larger than the orbital limiting field for $H \parallel c$ but smaller than the $H \perp c$ case. The corresponding Maki parameter $\alpha = \sqrt{2}H_{c2}^{\text{orb}}(0)/H_p$ is $\alpha = 1.99$ and 1.31 for $H \perp c$ and $H \parallel c$, respectively. This observation indicates that the $H_{c2}(0)$ values in both directions are determined by the Pauli limiting effect while $H_{c2}(0)$ along $H \perp c$ is more severely limited and the $H_{c2}(0)$ along $H \parallel c$ is enhanced beyond the BCS prediction possibly due to spin-orbit coupling. Therefore, to fully explain the temperature dependence of H_{c2} for each field direction, one might have to consider the interplay between the Pauli and orbital limiting mechanism in the two-band system.

In summary, we find that a single crystal of $\text{SrFe}_{1.85}\text{Co}_{0.15}\text{As}_2$ shows nearly isotropic $H_{c2}(0) \approx 48$ T in both crystallographic direction parallel and perpendicular to c -axis, suggesting that the Pauli limiting effect should be also considered, in addition to the conventional orbital limiting effect in a multiband system.

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- [1] Y. Kamihara *et al.*, J. Am. Chem. Soc. **130**, 3296 (2008).
- [2] H. Q. Yuan *et al.*, Nature **457**, 565 (2009).
- [3] S. Baily *et al.*, Phys. Rev. Lett. **102**, 117004 (2009).
- [4] J. S. Kim *et al.*, J. Phys.: Condens. Matter **21**, 102203 (2009).
- [5] H.-J. Kim *et al.*, Phys. Rev. B **79**, 014514 (2008).